DEVELOPMENT OF HIGH SPEED ALTERNATOR FOR SMALL GAS TURBINE ENGINE

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ABSTRACT

A high-speed alternator is deigned and experimentally evaluated for its performance with load. For testing the alternator a partial admission turbine drive is optimally designed and fabricated. The turbine drive system is analyzed for stresses and critical speed. The alternator, which consists of permanent magnet surrounded by a stator, was designed to get the required power. The alternator was tested at various speeds with load. This paper describes the salient features of the alternator and its performance characteristics.

NOMENCLATURE

B_{av}	Average Flux density in the core (Tesla)
C_0	Output coefficient = 11 $k_w B_{av}$ q x 10^{-3}
D	Diameter of the alternator inner (mm)
d_s	Depth of the slot (mm)
d_c	Depth of stator core (mm)
E_{ph}	Induced emf per phase (volts)
K_w	Winding Factor
K_p,	Pitch factor
K_d	Distribution factor.
L	Length of the alternator (mm)
N_S	Speed of the alternator (rps)
Q	Capacity of the alternator (KVA)
q	Specific electric loading (ampere conductors per meter)
S	Number of stator slots.
T_P	Pole pitch.
Φ	Flux per pole (Wb)

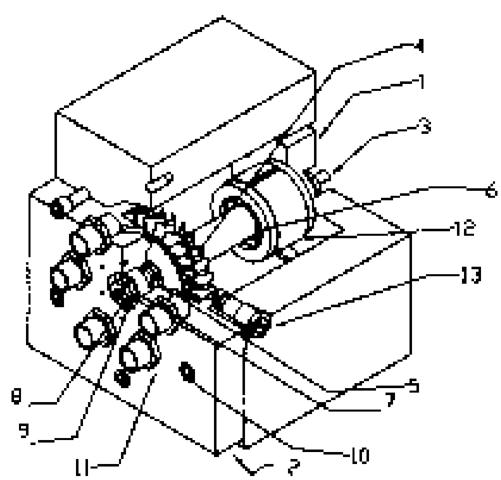
INTRODUCTION

Small Gas turbine engines are used in unmanned aerial vehicles and auxiliary power units for aircrafts. The engine used in the above applications should have low specific weight and high power to weight ratio. Hence any onboard power to the accessories of the engine should be derived from a small generator mounted on the same shaft. This makes the generator to run at high speeds and compact. Usually the generator will be mounted in between two stages of the compressor so that the compressed air will be used to cool the stator windings of the generator. Most of the technical data on such small generator is restricted and one needs to derive generator data from experimental tests through iterative trails. This paper describes the salient design features of the high-speed generator used in small gas turbine engine and experimental analysis to evaluate the performance of the generator. This paper also describes the design and evaluation of air turbine used to drive the generator.

A partial admission air turbine drive is used to drive the generator at various speeds. The rotor system of the drive is optimized mechanically to run without any vibration. A 2 kW generator is designed and fabricated in-house. The generator designed has a variable output voltage and variable frequency with respect to speed. The rotor is made up of permanent magnets, which can withstand high temperature and the North and South poles are mounted in the usual manner. The stator of the generator is made up of stacked thin metal sheets cut to the desired shape. Measurements were carried out by varying the load through passive device. The results of the measurements are discussed in this paper.

TEST SETUP

A partial admission air turbine drive is designed and fabricated to drive the generator at various speeds. Controlling the backpressure varies the speed of the generator. The complete rotor system has been analyzed for critical speeds and stresses. The rotor system is optimized mechanically by varying the positions of the bearings, rotor and generator. The estimated critical speed is well above the operating speed and the stresses are below the yield value of the material. The designed and fabricated air turbine serves as a variable speed drive for the generator. The schematic layout of the drive system along with generator is shown in Figure-1. The generator rotor is mounted on the same shaft. The exit air from the turbine is made to pass through the stator coil, which surrounds the rotor to take away the heat generated in the windings. A uniform clearance between the rotor and stator is maintained. The stator of the alternator is made up of stacked thin metal sheets cut to the desired shape. The stator material is selected so as to have low hysteresis and eddy current losses.



1. Outer Casing
2. Outer Cover
3. Shaft
4. Turbine Rotor
5. Lock Nut
6. Stator Assembly
7. Bearing
8. Nut
9. Nut
10. Allen Bolt
11. Connector
12. Rotor Assembly
13. Probe Assembly

Figure-1 Schematic Layout of Drive System for Alternator

INSTRUMENTATION

Measurements were taken by varying the load through passive device. For each load the generated voltage and load current were measured in each phase over duration of 20-30 minutes. The phase voltage and load current were measured in all the three phases by digital volt/ampere meters. During the measurements an eddy current probe was used to monitor the speed of the turbine rotor continuously. Thermocouples were also embedded in the windings to monitor the temperature rise. To get better control over the speed with load, it is planned to have pressure regulator in the inlet air jets. The conversion from AC to DC voltage will be carried out using the switch mode power supply circuits. The alternator designed will have a variable output voltage and variable frequency with respect to speed.

DESIGN OF PARTIAL ADMISSION TURBINE

A partial admission turbine is designed and manufactured using CNC machine. The turbine rotor is aerodynamically designed to get the required power at the specified speed. The typical values of percentage admission, specific speed and specific diameter of the turbine are assumed for the design. The design was carried out through iterative trails by varying the rotor geometry to get the required power [1.2]. The various losses like windage loss, expansion loss, end of sector loss and disk friction loss were estimated at the design point to validate the assumed efficiency. The number of blades for the turbine rotor is estimated by considering the minimum cutter size available for machining the rotor. The inlet nozzle before the rotor is also suitably designed to get the required inlet flow angle to the rotor. The designed parameters of the turbine are

Specific speed	0.18 (Non-dimensional)
Specific diameter	4.5 (Non-dimensional)
Percentage admission	30 %
Overall Efficiency	70 %
Speed	30,000 rpm
Tip Diameter	100 mm
Blade Chord	17 mm
Blade Height	15 mm
Number of Blades	27

The various losses were estimated to calculate the assumed efficiency. The typical losses at design point are

Windage losses	0.388 kW
Expansion Loss	0.113 kW
End of Sector Loss	0.258 kW
Disc Friction Loss	0.000319 kW

The geometrical co-ordinates for the turbine blade are generated in AutoCAD and used for machining the blades using 3-axis CNC milling machine. The turbine disc was analyzed for stresses due to centrifugal and gas loads and optimum geometry of the disc and blade thickness were obtained. The rotor system was also analyzed for critical speed.

The first critical speed was made above 50,000 rpm by adjusting the bearing, rotor and generator locations.

DESIGN OF ALTERNATOR

A synchronous machine (alternator) consists of two major parts namely the armature and the field system. In this system the armature is in the stator and the field system is in the rotor.

Stator

The stator is made up of laminations of special silicon steel alloys having slots on the inner periphery to accommodate the conductors called windings. Since the rotor rotates within the stator the flux from the rotor cuts the windings in the stator, producing the induced electromotive force in the windings of the stator. The stator core is laminated and insulated from each other with silicon-oxide coating to minimize the eddy current losses. After the windings the stator assembly is impregnated with insulating varnish.

The main dimensions of the alternator can be calculated by using the out-put equation which is given by[3]

$$\mathbf{Q = C_0 D^2 L N_S}$$

For circular poles, $\mathbf{L = 0.6 - 0.7\, T_P}$

Co, which depends on specific electric loading. With higher values of specific electric loading the copper losses will be more and also the temperature rise will be higher. However the synchronizing power and stability is small. Typical values specific electric loading for non-projecting pole type alternator is in the range of 50,000 to 75,000 Ampere conductors/m

NUMBER OF SLOTS

The number of armature slots must be such that a balanced winding should be obtained. With less number of slots conductors per slot will be more and internal temperature rise will be high. Whereas, with more number of slots tooth ripples will be less in the field form and also width of the teeth will be less with higher iron losses. Therefore optimum values for slot pitch should be selected. It is usually selected based on experience. In general the recommended value of slot pitch should be less than 25mm for small machines.

The number of turns per phase, $\mathbf{T_{Ph}}$ is calculated using

$$\mathbf{E_{Ph} = 4.44\, f\, T_{Ph}\, \varphi\, K_P\, K_d}$$

Where $\varphi = B_{av}\, T_p\, L$

Stator core outer diameter of the machine = $(D + 2d_s + 2d_c)$

STATOR SLOT DIMENSION

The dimensions of the slot determine the value of flux density in the teeth. A high value of flux density in the teeth is not desirable, as it leads to a higher iron loss and a greater magnetizing magneto motive force (mmf). The slot dimensions like width and depth is determined by the empirical formulae taken from the design book [3]

The minimum width of the tooth, y_{ss} is given by

$$y_{ss} = (\pi D/S)$$

ALTERNATOR ROTOR

The alternator rotor, which is a rotating component basically, consists of four permanent magnets enclosed in a cylindrical titanium steel ring. The magnet is held in position by screwing two end washers to the steel ring. Rare earth alloy samarium cobalt is used for the magnets[4]. This magnet has been selected due to its merit in the magnetic properties and higher working temperature of the order of 200ºC. The magnet is positioned inside the steel ring in such a way to get a proper polarity and constitutes a four-pole rotor.

By knowing the flux density and the area of cross section of the rotor per pole we can determine the flux. While determining this flux it is assumed that the flux leakage factor of around 1.15 to 1.2. The permanent magnet is designed to get minimum volume by maximizing the BH product. The typical values for the selected magnet[4] are around 135 kJ/m^3. This is carried out through iterative trails.

EXPERIMENTAL RESULTS

The high-speed generator is mounted on the common shaft between two ends of the bearing and a power turbine. The power turbine is driven by, impinging compressed air on the turbine blades. The outlet air passes over the stator winding of the generator and provides necessary cooling. The generator is capable of running at different speeds by adjusting the inlet air pressure. The generator is electrically loaded by providing external resistive load. The three phase windings have been terminated externally for connecting to the load. The load current and load voltage is measured using digital ammeters and digital voltmeters, which are connected to the load. The experiments were conducted for different speeds and the speed is fairly kept constant with load by adjusting the pressure. The generator is loaded for a specific time and the thermocouples embedded into the stator windings monitors the windings temperature rise. The voltage and current were also measured and recorded. Table-I gives the load current, phase voltage, line voltage, speed of the generator and the total power. The values for different speeds are indicated in this table. The last line in this table indicate the no load values of terminal voltage for 30,000 rpm (approx). It is observed from this table that more than a kilo Watt power is generated at 30,000 rpm (approx).

Table–II gives the performance characteristics values of the generator. This table provides the information of variation in power and temperature rise under load with time. From this table a variation of load current, phase voltage, total power, turbine inlet pressure and rise in winding temperature are plotted against time. This is shown in Figure-2.

The graph shows the time Vs load current, phase voltage, total power, turbine inlet pressure, speed of the generator in rpm and rise in winding temperature in degree C. From this graph we can say that we can draw a constant power of ~ 0.825 kW continuously and the rise in temperature is almost constant of 14^{o}C.

The phase voltage signals were captured with respect to star point simultaneously using the digital CRO. The recorded signals are shown in Figure-3. The R and Y phase voltage signals were captured first and then Y and B phase voltage signals were captured later while the generator is running continuously at a constant speed. It is observed from this figure, the phase difference from one phase to the other phase is exactly 120^{o} and pattern of the waveform is sinusoidal. There is a small distortion in the signal, which is due to the slight damage of the magnet at the edge during assembly.

CONCLUSIONS

The phase voltage, line current, winding temperature rise, speed of the alternator and air inlet pressure to the turbine have been noted during the experiment and the wave forms of the phase voltages and line voltages captured during the experiment are shown. The total power is computed and included in the tabulation. Further work has to be done for running the generator at higher speed and corrective design, and development work for the same to be done.

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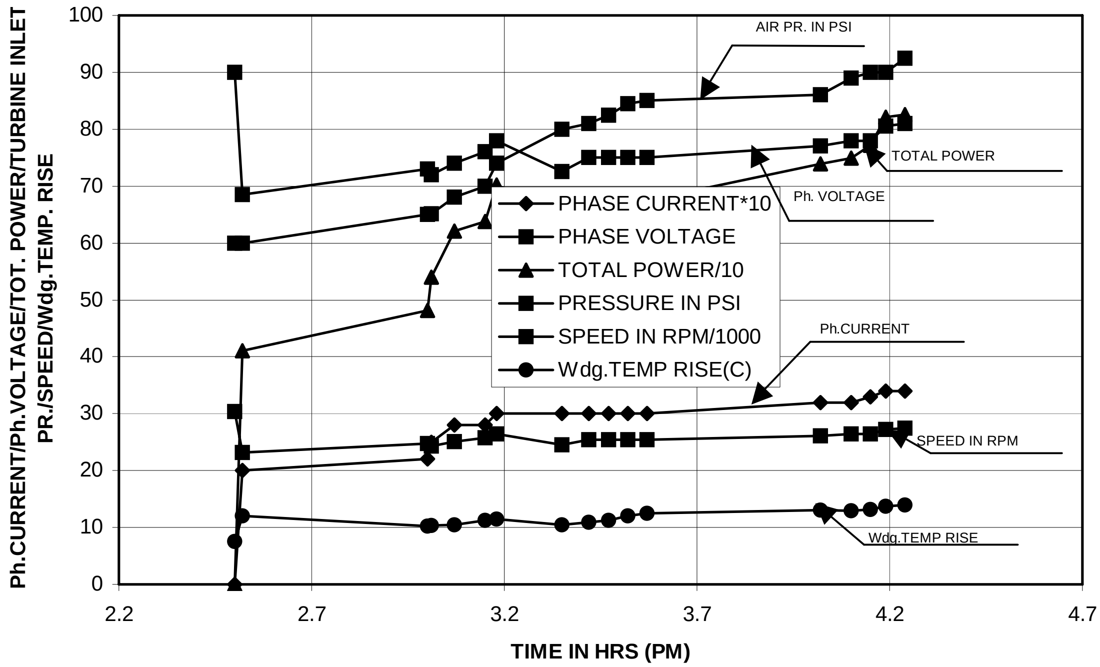

Figure-2 Performance Characteristics of 3 Phase Alternator

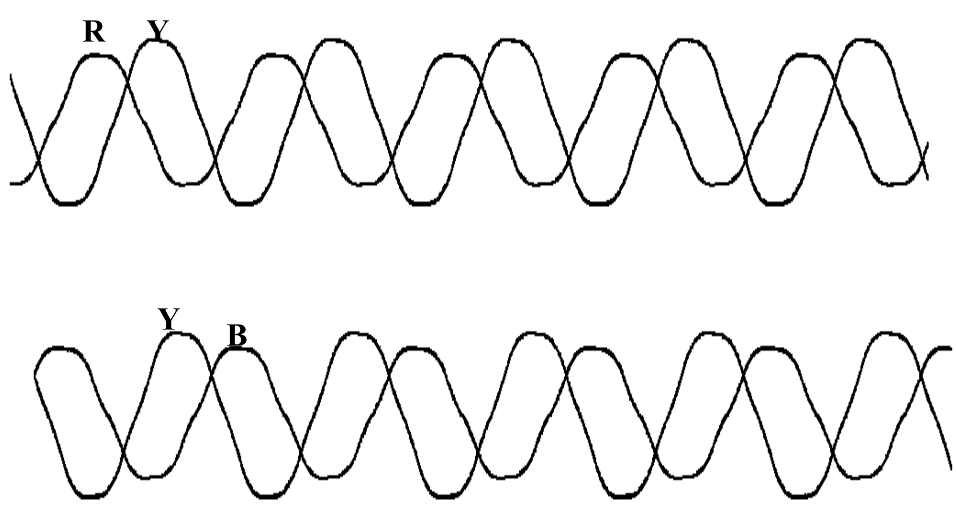

Figure-3 Measured wave forms w.r.t Star Point from Alternator

Table-I Variation of Phase Voltage, Phase Current and Line Voltage

Load Current in AMPERES	Phase Voltage in VOLTS	Line Voltage in VOLTS	Speed in RPM	Total Power in Watts
4.0	94	122	30900	1128
4.1	92	120	30900	1131
4.4	92	~120	30900	1214
3.4	81	140	27410	826
3.4	81	138	27241	821
3.3	78	136	26395	772
3.2	78	135	26395	748
3.2	77	131	26056	739
3.0	75	130	25380	675
3.0	75	130	25380	675
3.0	75	129	25380	675
3.0	75	130	25380	675
3.0	73	125	24534	652
3.0	78	135	26395	702
2.8	76	133	25718	638
2.8	74	130	25041	621
2.5	72	125	24364	540
2.2	73	128	24703	481
2.0	69	120	23180	411
0.0	90	158	30456	000

Table-II Performance Characteristic Data for Generator

Time In Hours	Load Current In Amperes *10	Phase Voltage In Volts	Total Power In Watts /10	Turbine Inlet Pressure In PSI	Speed In RPM/1000	Winding Temperature Rise In Deg.C
. 2.5	0	90.0	0	60.0	30.40	7.5
2.52	20	68.5	41.1	60.0	23.18	12.0
3.00	22	73.0	48.1	65.0	24.70	10.3
3.01	25	72.0	54.0	65.1	24.30	10.4
3.07	28	74.0	62.1	68.0	25.04	10.5
3.15	28	76.0	63.8	70.0	25.71	11.3
3.18	30	78.0	70.2	74.0	26.39	11.5
3.35	30	72.5	65.3	80.0	24.53	10.5
3.42	30	75.0	67.5	81.0	25.38	10.9
3.47	30	75.0	67.5	82.5	25.38	11.3
3.52	30	75.0	67.5	84.5	25.38	12.0
3.57	30	75.0	67.5	85.0	25.38	12.5
4.02	32	77.0	73.9	86.0	26.05	13.0
4.10	32	78.0	74.9	89.0	26.39	12.9
4.15	33	78.0	77.2	90.0	26.39	13.2
4.19	34	80.5	82.1	90.0	27.24	13.8
4.24	34	81.0	82.6	92.5	27.41	14.0